

Yield characteristics of N-S oriented olive hedgerow orchards, cv. Arbequina

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ABSTRACT

Profiles of yield (g oil m^{-2}) and yield components, fruit density (m^{-2}), size as dry weight (DW) (g), and oil% DW were measured in 11 N-S oriented hedgerow orchards, cv. Arbequina, of various height and alley width combinations in Spain. Profiles of daily shortwave solar radiation incident vertically on the canopy walls (MJ m^{-2}) calculated by a canopy illumination model were weakly exponential, revealing the importance of alley width in determining the diurnal persistence of sunlit canopy wall to depth. Strong positive linear relationships were established between radiation incident on canopy walls and fruit size and oil% over the entire canopy depth in all orchards. In contrast, fruit density was closely related to incident radiation on canopy walls only in the lower profile where incident daily solar radiation was $<6 \text{ MJ m}^{-2}$ during oil production in October. The consequence was a weaker relationship between yield (g oil m^{-2}) and incident radiation on canopy walls than between the size and oil% components. Explanation is found in the impact of pruning applied to maintain hedgerow height that removes fruit in the current year. Results emphasize the importance of alley width:height relationships in determining complete illumination of canopy walls in hedgerow orchards giving guidance to questions of optimal orchard structure for maximum yield. They also demonstrate importance and need for work on canopy management to maintain yield in upper canopies of hedgerows where fruit are large and also have high oil%.

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1. Introduction

Hedgerows are new production systems for olive. They are estimated to occupy 1% (100,000 ha) of a worldwide area of 10 Mha planted to olive. Although currently a small percentage, hedgerows are the most common orchard design in new plantings, especially in non-traditional production zones away from the Mediterranean Region. Advantages relate to ease of disease and pest control and to minimization of costs by mechanization of harvest and pruning. Tree densities are high, ranging from 400 to 1975 ha^{-1} , as is also cost of establishment, but this is compensated by early production, especially in orchards planted at high density.

Design and management of canopy structure are major concerns. An important question asks, for each location and grower, what is the optimum combination of row height, width and spacing to meet productivity, water requirement, and management objectives and capabilities? A second asks, how best to maintain optimum structure once has been achieved? Early experiences (Pastor et al., 2007) demonstrated changing patterns of fruitfulness

in developing hedgerows. Fruitfulness moved gradually higher as hedgerows grew taller, thus identifying the need to adjust canopy height to free alley width (i.e. row spacing minus row width), or vice versa, to provide adequate illumination of entire canopy walls. That aspect of optimum canopy structure was investigated with a light interception model (Connor, 2006) advising, as previously known for other hedgerow systems, apple (Cain, 1972) and wine grape (Smart and Robinson, 1991), that optimum structure for high productivity is found when the entire depth of canopy wall receives radiation above the threshold for fruitfulness. Applying a threshold radiation incident on canopy walls of 20% of horizontally incident radiation, as established for apple by Cain (1972), analysis revealed a solution for maximum productivity when free alley width was approximately equal to canopy depth. Observations on yield profiles in hedgerow olive orchards (Connor et al., 2009) have identified preliminary relationships between patterns of canopy illumination and yield components of various cultivars in hedgerows of various structures and orientations.

In this paper we re-analyze relationships between incident radiation and yield components in N-S oriented hedgerows of cv. Arbequina by adding new data to that previously presented in Connor et al. (2009).

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Table 1

Location and structural features of 11 N–S oriented olive hedgerow orchards, cv. Arbequina, and daily clear sky shortwave radiation during October.

Site number	Location	Shortwave radiation October ($\text{MJ m}^{-2} \text{d}^{-1}$)	Canopy					Number of layers
			Height (m)	Rows at (m)	Trees at (m)	Alley (m)	Alley/height	
1	El Carpio	16.7	2.0	3.0	1.35	2.1	1.1	5
2	El Carpio	16.7	2.4	3.0	1.35	2.1	0.88	6
3	El Carpio	16.7	2.8	3.0	1.35	2.1	0.75	7
4	Ecija	17.8	3.0	3.75	1.35	2.5	0.83	5
5	Toledo	16.7	2.0	4.0	1.50	3.3	1.5	4
6	Toledo	16.7	2.5	4.0	1.50	3.0	1.2	5
7	Ermita	16.7	2.8	3.0	1.35	2.1	0.75	4
8	Ermita	16.7	2.8	3.0	1.35	2.1	0.75	4
9	Pedro Abad	17.6	2.0	3.75	1.35	2.4	1.2	5
10	Pedro Abad	17.6	2.8	3.75	1.35	2.2	0.79	7
11	Pedro Abad	17.6	3.6	3.75	1.35	2.4	0.67	9

2. Materials and methods

2.1. Data collection

Measurements of fruit density, size and oil%, the latter two according to dry weight (DW), were made from fruit harvested manually by layers, mostly of 0.4 m depth but up to 0.7 m, in 11 N–S oriented orchards of varying height, width, and row spacing. All sites were in Spain, ranging from 37.5 (Ecija) to 39.9°N (Toledo). Values were analyzed as means of observations for individual layers taken from both sides of the central axes of the hedgerows, for which no differences were established.

Structural features of the orchards are summarized in Table 1. All were planted a high density with intra-row tree spacing of either 1.35 or 1.5 m. At the time of measurements all orchards formed continuous, essentially rectangular, hedgerows. Key comparators of orchard structure are height and alley width. Height ranges from 2.0 to 3.6 m and alley width from 2.1 to 3.3 m. The ratio alley width:height was from 0.67 to 1.65.

2.2. Analytical methods

2.2.1. Profiles of incident radiation on canopy walls

Incident radiation (Rad_{ij}) on canopy walls was estimated at the mid-point of each layer (j) of each orchard (i) according to horizontally incident daily shortwave radiation at each site (Rad_i) and corresponding alley width (see Table 1) using the canopy illumination model of Connor (2006) that accounts for penetration of direct beam solar radiation and diffuse sky radiation into alley spaces. A validation of the model has been presented in Connor et al. (2009). Vertical profiles of incident radiation on canopy walls for each orchard were then expressed as exponential functions according to Eq. (1). By that analysis, each orchard is distinguished by an extinction coefficient (k_i) that depends on alley width.

$$Rad_{ij} = Rad_i e^{-k_i \text{Depth}_{ij}} \quad (1)$$

2.2.2. Profiles of yield and yield components

Linear regressions of yield or yield components (Y_{ij}) on radiation incident on canopy walls (Rad_{ij}) were performed to calculate overall relationships with the site effect (S_i) introduced as an additive site specific factor and treated as a block in linear regression analysis (Eq. (2)). The slope b defines responses of yield or yield components to incident radiation by layers on canopy walls.

$$Yield_{ij} = S_i + bRad_{ij} \quad (2)$$

2.2.3. Effect of site on yield and yield components

A principal component analysis was made of values of the additive site specific factor (S_i) in regressions of yield and yield components on radiation incident on canopy walls (Eq. (2)). The

result is presented as a biplot that allows visual representation of differences between sites. On the one hand it reveals correlations between components of yield, and on the other, their association with sites.

2.2.4. Components as determinants of yield

Linear models were also used to determine individual effects of yield components on yield. First, simple linear regressions were applied in which site effects were introduced as blocks (Eq. (3)). The slope c defines responses of yield to yield components.

$$Yield_{ij} = S_i + cYield \text{ comp}_{ij} \quad (3)$$

Second, a multiple linear regression of yield vs. yield components was applied in order to identify the component with greatest impact on yield variation. For this, yield components were included progressively, if statistically significant, with a forward selection criterion.

All statistical analyses were carried out using R (R Development Core Team, 2008).

3. Results

3.1. Profiles of radiation incident on canopy walls

Results are presented for October that is an important month in fruit growth and oil production. Profiles of radiation incident on canopy walls of individual orchards, as presented together in Fig. 1. They are exponential in form with individual extinction

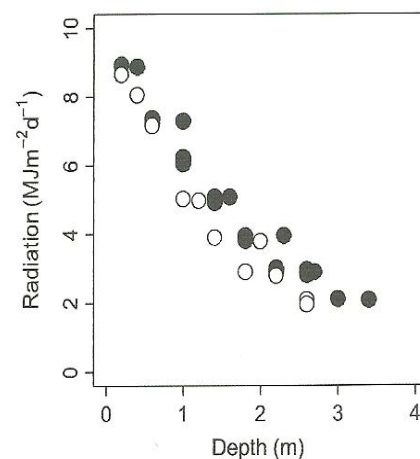


Fig. 1. Vertical profiles of daily shortwave radiation incident on canopy walls of various N–S olive hedgerow orchards on clear sky days during October at ca. 39°N. Open circles distinguish observations with larger extinction coefficients at sites 1, 2, 3, 7 and 8.

Table 2

Site specific exponential extinction coefficients (k_i) for profiles of radiation incident on canopy walls (Eq. (1)) and values of site specific additive factors (S_i) of yield and yield components profiles (Eq. (2)) for olive orchards at 11 sites.

Site	k	Values of site specific additive factors			
		Yield (g oil m ⁻²)	Density (m ⁻²)	Size (g)	Oil% (%DW)
1	0.70 c	-98.0 c	-341 b	0.37 bc	32.7 d
2	0.61 b	-54.6 d	-93.8 c	0.34 c	33.5 d
3	0.60 b	-23.4 d	197 d	0.32 b	32.2 d
4	0.49 a	-93.3 c	-228 bc	0.35 c	32.2 d
5	0.46 a	-139 b	-642 b	0.36 c	36.8 f
6	0.50 a	-138 b	-600 b	0.38 d	36.1 f
7	0.60 b	-92.4 d	-190 bc	0.31 b	29.4 c
8	0.60 b	-115 bc	-525 b	0.41 d	34.8 e
9	0.50 a	-218 a	-814 a	0.18 a	27.8 b
10	0.51 a	-170 b	-520 b	0.19 a	26.1 a
11	0.48 a	-113 bc	-354 b	0.29 b	32.0 d
LSD ($p=0.05$)	0.047	37.9	228	0.024	0.89

coefficients (k_i , Eq. (1)) in the range 0.48–0.70, and with an average value of 0.53 ($R^2=0.94$) when analyzed individually. These values are presented in Table 2. The variation in k for alleys of equal width (e.g. 2.1 m, see Table 1) arises because profiles of intercepted radiation were calculated for harvested layers of different depths, leading to different precision in establishment of the exponential function. Results reveal that extinction coefficients for orchards at sites, 4–6, with wide alleys (>2.5 m), and therefore with most illuminated canopy walls, are significantly smaller than those at other sites. These data are included as column 2 in Table 2. Responses in all orchards are substantially linear in the top 2.5 m of the canopies.

3.2. Yield profile

Profiles of yield, g oil m⁻², are presented according to radiation incident on canopy walls in Fig. 2. There is no evident relationship in upper canopies where incident daily radiation on walls exceeds 6 MJ m⁻². This zone corresponds to ca. the upper 0.5 m of hedgerows with mean alley width. Below that depth, however, results reveal a strong linear relationship of yield with radiation incident on canopy walls. Observations were available to 2 MJ m⁻² in some canopies. In those parts of canopies, a strong linear trend applies to all orchards ($R^2=0.45$) with a slope (b) of 50.5 g m⁻² MJ⁻¹ m² d. When orchards are analyzed individually, i.e. they are included as random blocks in Eq. (2), the overall fitted relationship with $R^2=0.79$ reveals that all orchards display strong individual linear trends but with differences in actual yields. At sites 5, 6, and 9, oil yields are below the average for all sites taken together, i.e. they are below average for the same levels of radiation incident on canopy walls (Table 2, column 3).

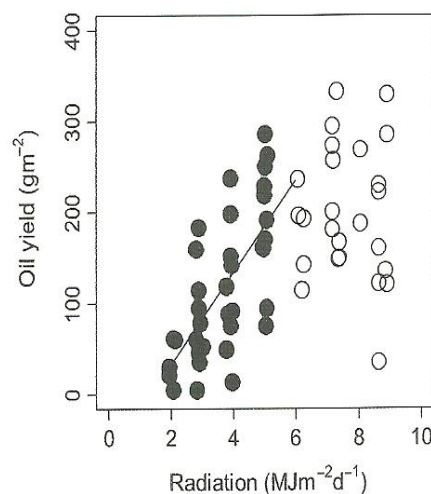


Fig. 2. Profiles of oil production per unit canopy surface area according to daily incident shortwave radiation by depth in various N-S hedgerow olive orchards, cv. Arbequina. Open circles are used to distinguish observations in upper canopies where daily incident radiation exceeds 6 MJ m⁻². The fitted line to all observations in lower canopies has a slope of 50.5 g m⁻² MJ⁻¹ m² d ($R^2=0.45$). Linear responses to each orchard have a combined $R^2=0.79$.

3.3. Profiles of yield components

Density, size, and oil% of fruit are plotted against radiation incident on canopy walls in Fig. 3. The relationships reveal variability between orchards but, with effect of site included, consistently decreasing density, size and oil% with incident radiation.

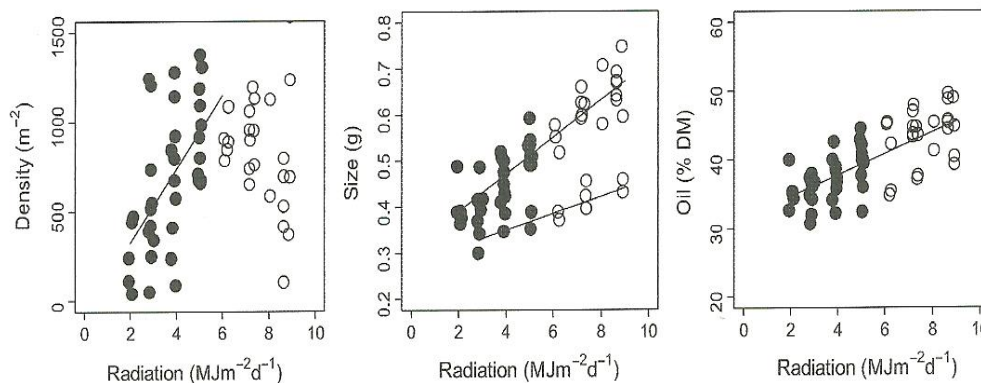


Fig. 3. Profiles of yield components, density, size (DW), and oil content (%) of fruits, according to daily incident shortwave radiation by depth in various N-S hedgerow olive orchards, cv. Arbequina. Open circles are used to distinguish observations in upper canopies where daily incident radiation exceeds 6 MJ m⁻².

There is great variability in fruit density in the upper profile, where daily incident radiation $>6 \text{ MJ m}^{-2}$, but below that density decreases linearly with incident radiation, slope: $206 \text{ MJ}^{-1} \text{ m}^2 \text{ d}$ with adjusted $R^2=0.30$. When sites are introduced into the model to account for differences in radiation and reproductive profiles, analysis reveals strong individual linear relationships with an overall $R^2=0.71$. For similar incident radiation, sites 1, 5, 6, 8, 10 and 11 have fruit densities significantly below the overall mean (Table 2, column 4).

Size is characterized by two strong linear relationships with incident radiation over entire canopies. Taken all together, size decreases with incident radiation at $0.034 \text{ g MJ}^{-1} \text{ m}^2 \text{ d}$ ($R^2=0.48$). Taking sites into account, the linear relationship is strengthened with adjusted $R^2=0.92$. As presented in Fig. 3b, two orchards, 9 and 10, are distinct with consistently smaller fruit and smaller decrease in size in response to decreasing incident radiation ($0.018 \text{ g MJ}^{-1} \text{ m}^2 \text{ d}$, $R^2=0.78$) than the remaining nine sites ($0.040 \text{ g MJ}^{-1} \text{ m}^2 \text{ d}$, $R^2=0.80$). Sites 9 and 10 are distinct with significantly smaller fruit despite comparable levels of incident radiation (Table 2, column 5).

Oil% also decreases consistently with decreasing radiation incident over entire canopy profiles. Overall response is $1.55 \text{ MJ}^{-1} \text{ m}^2 \text{ d}$ ($R^2=0.52$) with stronger individual linear relationships in individual orchards ($R^2=0.94$). For the same incident radiation on canopy walls, oil% at sites 7, 9 and 10 is below average.

3.4. Effect of sites on profiles of yield and yield components

The biplot of principal components of data in columns 3 and 6 of Table 2 summarizes site effects (S_i) on profiles of yield and yield components. For lower canopies, where daily incident radiation $<6 \text{ MJ m}^{-2}$, it explains 97% of variation, 63% in the first principal component (PC1) and 34% in the second (PC2).

This form of analysis, as presented in Fig. 4 reveals differences between orchards. Those in the centre of the map (1–4, 7 and 11) are close to the mean values of yield and yield components of the complete data set. Those away from the centre differ in certain characteristics.

The map reveals that sites with fruit size above average also have above average oil%. It also reveals the limited relationship between the vector pairs fruit size and oil% and density and yield, which in the biplot, are almost at right angles to each other. The map shows that sites with above average yields are more associated with above average fruit density than large fruit size or oil%. Thus, sites 5, 6 and 8 have large fruit and highly correlated large oil%, but also small fruit density. Sites 9 and 10 are characterized by small fruit size and oil%.

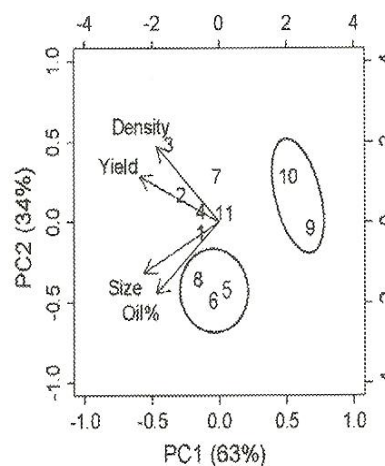


Fig. 4. Principal component analysis as a biplot of site effect on profiles of yield and yield components (Table 2). Yield and yield components are represented by arrows and sites by numbers.

3.5. Components as determinants of yield

In Fig. 5, each component of yield, viz. density, size and oil%, is plotted against the product, i.e. oil yield m^{-2} canopy surface. Where daily incident radiation on canopy walls is $<6 \text{ MJ m}^{-2}$, analysis reveals strong positive correlations between oil yield and each component of yield, as follows.

Density: Oil yield increases with density. The overall response, $0.20 \text{ g m}^{-2} \text{ m}^2$ ($R^2=0.81$), is increased slightly by introducing site into the analysis ($R^2=0.87$).

Size: Oil yield increases with size. The overall response, $776 \text{ g m}^{-2} \text{ g DW}^{-1}$ ($R^2=0.50$), is increased significantly by introducing site into the analysis ($R^2=0.79$).

Oil%: Oil yield increases with oil%. The overall response, $14.3 \text{ g m}^{-2} \text{ g DW}^{-1}$ ($R^2=0.41$), is increased significantly by introducing site into the analysis ($R^2=0.72$).

Multiple linear regression analysis of contributions of yield components to oil yield reveals that differences in density most strongly explain the variation in yield between layers and sites. Together, size and density explain the major part of variation ($R^2=0.96$), a result that can be explained by close relationship between oil% and fruit size, indicated previously (Fig. 4), and discussed in the following section.

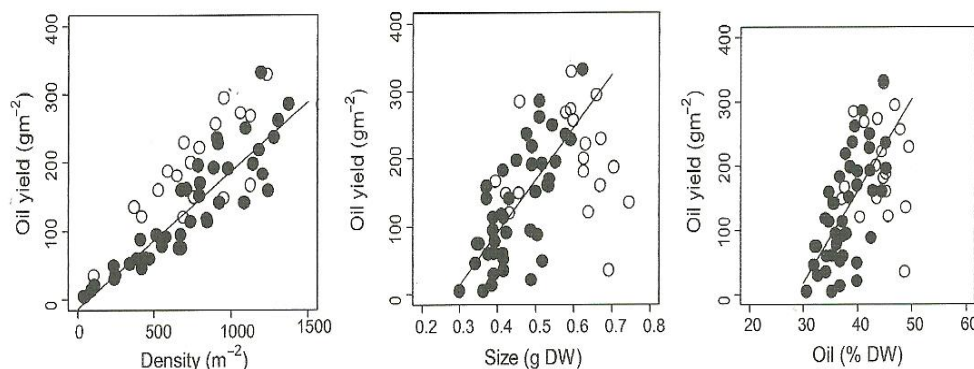


Fig. 5. Relationship between oil yield and its components for various N-S hedgerow olive orchards of cv. Arbequina in Spain. Open circles are used to distinguish observations in upper canopies where daily incident shortwave radiation exceeds 6 MJ m^{-2} .

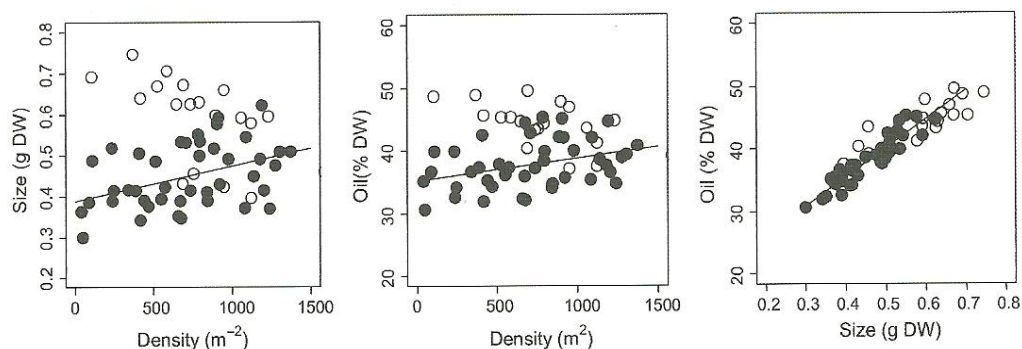


Fig. 6. Relationships between size, oil%, and density for fruit harvested at maturity from various positions in various N–S olive hedgerow orchards, cv. Arbequina, in Spain. Open circles are used to distinguish observations in upper canopies where daily incident shortwave radiation exceeds 6 MJ m^{-2} .

3.6. Relationships between yield components

Comparison of three graphs that comprise Fig. 6 reveal no overall relationship between either size and density ($8.5 \times 10^{-5} \text{ g DW m}^{-2}$, $R^2 = 0.15$) or oil% and density ($0.004\% \text{ DW m}^{-2}$, adj. $R^2 = 0.11$) but a strong relationship between oil% and fruit size (adjusted $R^2 = 0.87$, slope: $41.2\% \text{ g}^{-1} \text{ DW}$).

4. Discussion

4.1. Radiation profiles

The profile of radiation incident downwards from the top on canopy walls in N–S hedgerows orchards depends upon alley width and is dominated by direct solar radiation because diffuse radiation from the entire hemisphere forms a small part of incident solar flux (10% on clear days) and less is directed into alleys. Length of sunlit canopy increases from zero at sunrise to a maximum on eastern sides of N–S oriented orchards determined by alley width, day of year and latitude, then after noon switches to western sides, decreasing from the same maximum to zero at sunset. Where canopy walls are sunlit, they receive equal direct radiation at all depths so that total daily incident radiation depends largely on the duration with depth of length of sunlit wall (Connor, 2006). Upper parts of canopies that are separated by similar alley width receive similar patterns of diurnal illumination independently of height. Tall canopies, however, have increasing proportions of lower canopy that receive either little, or no, direct radiation, and that is exacerbated at narrow alley width. This helps explain the nature of the radiation profiles presented in Fig. 1. Profiles are relatively similar in the upper canopy but, given the range of alley width (2.1–3.3 m), they diverge at depth. Limited interception at depth in tall canopies (relative to alley width) establishes the exponential nature of the overall expression (Eq. (1)) used to analyze fruit response data in this paper.

4.2. Profiles of yield and yield components

Explanation of the relationship established between oil yield and incident radiation down canopy walls (Fig. 2) is found in responses of individual yield components presented in Fig. 3. Strong positive linear relationships exist over entire canopies between incident radiation and both fruit size (Fig. 3b) and oil% (Fig. 3c). By contrast, linear relationships between fruit density and incident radiation hold only in lower canopies where daily incident radiation $< 6 \text{ MJ m}^{-2}$. Above that level, i.e. in the top ca. 0.5 m, relationships are highly variable and contribute to yield variation between canopies, including those of similar alley width:height ratio.

4.3. Components as determinants of yield

Of the three components of yield, density exerts most control on yield, i.e. explains most variation between orchards ($R^2 = 0.87$). Fruit size is the next most important, and taken together with density, explains 96% of variation in yield between orchards. That statistical result is determined by the strong relationship ($R^2 = 0.87$) established between oil% and the wide range of fruit size (Fig. 4c). As for other relationships between yield components, none was found between fruit size and density, as might be expected where yield is source limited at low levels of incident radiation. In these orchards, density and fruit size decreased together in lower canopies without evidence of fruit loss that could maintain large fruit size.

The strong relationship between fruit size and oil% deserves comment. In these data, progressively larger fruit found towards tops of canopies also had greater proportions of oil. This positive relationship is readily explained. Oil is formed mostly within pulp during the second stage of growth when pit development is complete. Fruits then enlarge by adding pulp and storing oil, up to 50% fruit DW in these data, so consequently the proportions of pulp and oil increase with fruit size and that of pit is reduced (Lavee and Wodner, 2004; Rapoport, 1998; Gómez-del-Campo and Rapoport, 2008).

4.4. Production profile and the requirements for high yield

The study has shown that a major part of productivity of a range of hedgerow olive orchards, cv. Arbequina, can be related to patterns of solar radiation intercepted by the canopy walls. Fruit size and oil% down canopy walls were found to be closely and linearly related to incident radiation. Fruit density, the remaining yield component was also linearly related to incident radiation but only in lower parts of canopies, where daily incident radiation was $< 6 \text{ MJ m}^{-2}$. In upper parts, comprising ca. 0.5 m depth in canopies of average alley width (2.5 m), there was no relationship; both high and low densities were recorded at similar values of incident radiation. Oil yield fell to zero when daily incident radiation on the walls was around 2 MJ m^{-2} in the least well illuminated orchards, i.e. about 12% of horizontally incident radiation at the site. The main yield determinant in that response was fruit density (Fig. 3a).

October is an important month in fruit growth and oil formation at latitudes of these experiments. Determination of fruit density is a more prolonged affair with steps commencing in the previous year associated with shoot growth, apex differentiation, flower formation, flowering, fruit set, and fruit retention and is also subject to other environmental influences such as cold and hot temperature, wind, hail, frost and diseases. Given that, a question arises if the response of fruit density to incident radiation in October

established in the lower canopy was perhaps fortuitous? Impact of extreme events apart, three comments may be useful. First, although quantitatively different, patterns of incident radiation on N-S hedgerows remain relatively constant during the year (Connor, 2006), so correlated responses to radiation are possible. Second, fruit density is highly responsive in olive with fruit-fall adjustments being characteristic right through to mid fruit growth (Rapoport, 1998; Gómez-del-Campo and Rapoport, 2008). And third, this analysis made allowance for differences in yield components, including density, between orchards that reflect impact of factors other than intercepted radiation.

Even so, the variable nature of fruit density in the upper canopy complicates establishment of general relationships of yield with canopy structure. While the study provides guidelines for yield in lower canopy in response to shading determined by alley width:height relationships, it is clear that high orchard yields also require major contributions from upper canopies. That is possible because largest fruit are found there and, within individual cultivars, large fruit have high oil%. The question is what controls fruit density in the most rapidly growing part of these hedgerow canopies? A dominant part of the answer is found in canopy management undertaken to maintain structure. Topping, for example, results in strong vegetative growth in tops of canopies that cannot flower and fruit until the following year but in the meantime shade walls of adjacent hedgerows reducing yield there. This leads to the second part of the challenge of optimum structure of hedgerow orchards as explained in the introduction. Optimal height and alley width can only be maintained by intermittent pruning that changes the distribution of fruit production. Work is urgently required to understand how best to maintain fruitfulness in mature hedgerow canopies. Observations reported here emphasize importance of upper canopies to achievement of high orchard yield.

One application of relationships established between fruit size and oil content with incident radiation in this study is to make earlier and more accurate yield predictions to assist harvest planning. These are currently done with serial measurements of density, fruit

size, and oil content (Rius, 2008). Based on relationships established here between canopy structure and fruit yield characteristics, it appears that an opportunity exists to move more quickly and earlier to predictions based on fruit density measurements alone.

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